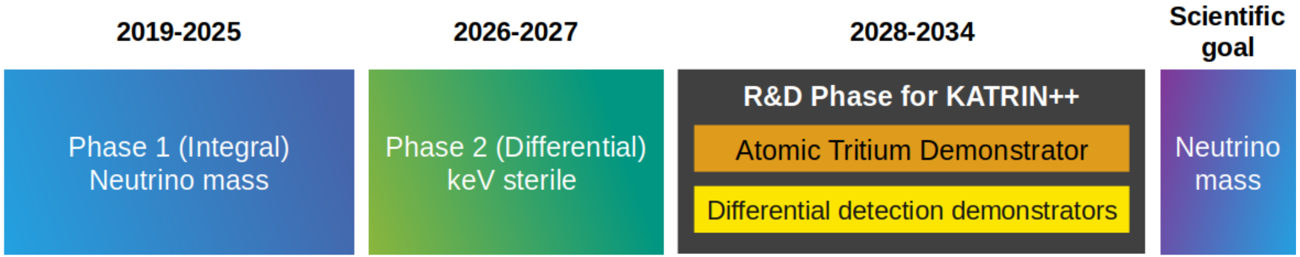
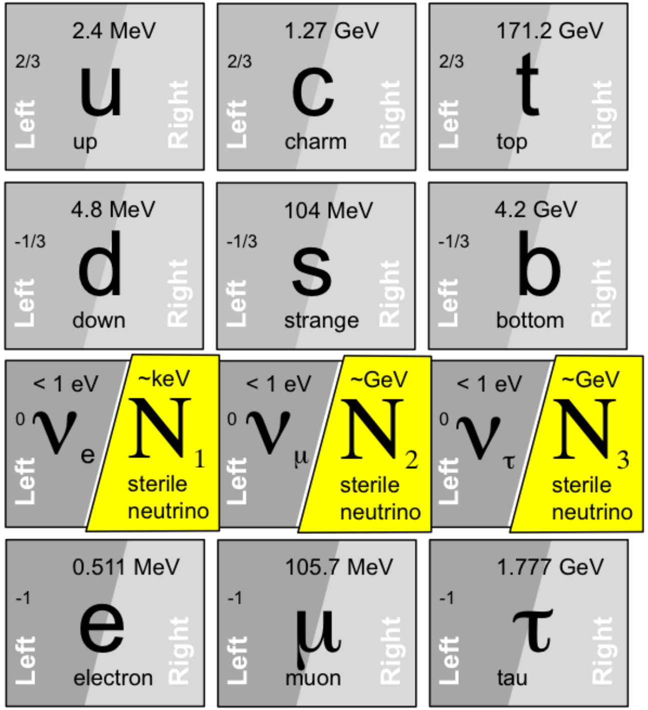
From KATRIN to KATRIN++

Markus Steidl. „Matter and the Universe“ Days 2024@DESY



ν – mass, a fundamental parameter



S.M. **with** a minimal extension

Key role for Standard Model:

→ Higgs mass mechanism of S.M. does not fit to neutrinos, right handed neutrinos would be minimal extension of S.M.

→ implications for extensions to the SM, such as seesaw mechanisms and leptogenesis.

Key role for cosmology

→ ν's are the most abundant massive particle in the Universe

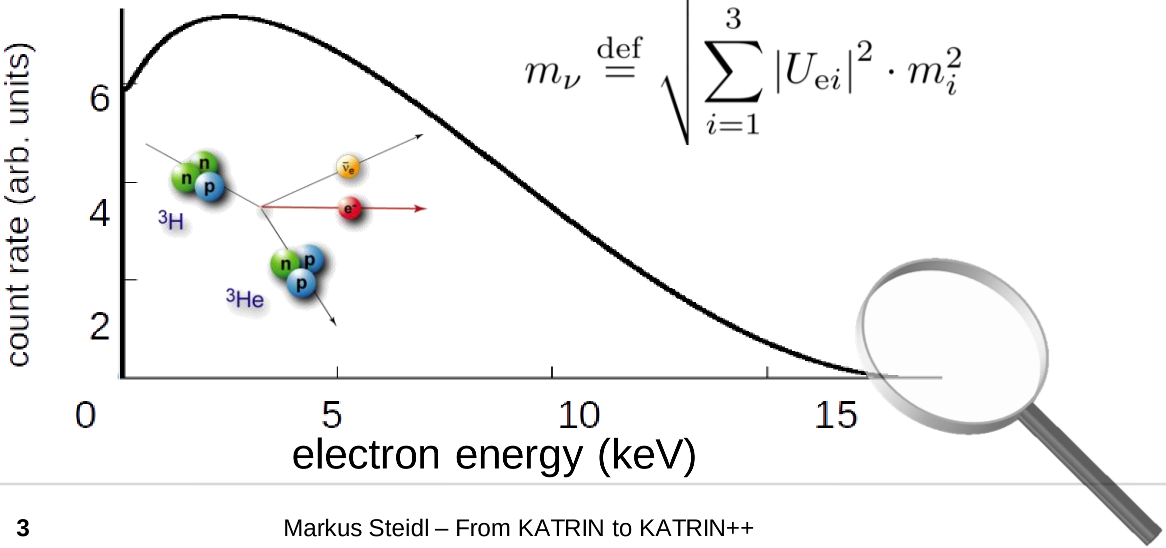
→ Neutrino masses impact cosmological evolutions (CMB, LSS, H_0 …)

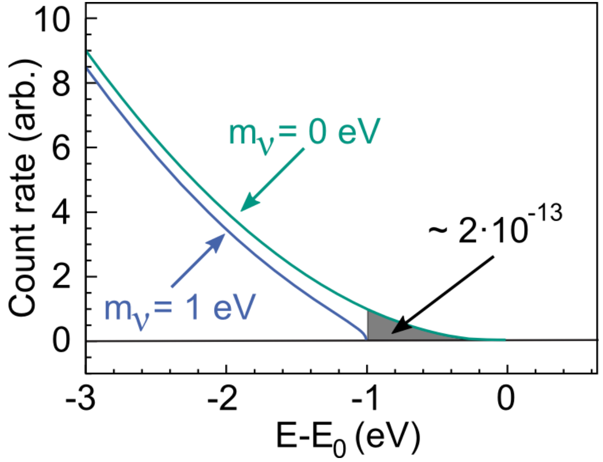
Neutrino mass in tritium β-decay

Measurement of effective mass m_ν based on **kinematic parameters & energy conservation**

$$R_\beta(E) \propto (E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}$$

$$m_\nu \stackrel{\text{def}}{=} \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$$



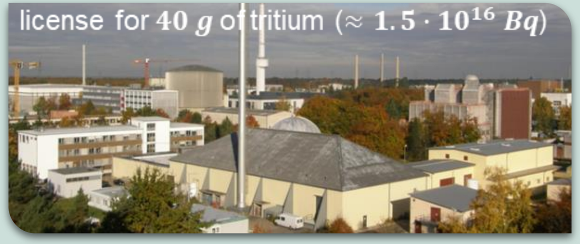


Neutrino mass in tritium β-decay

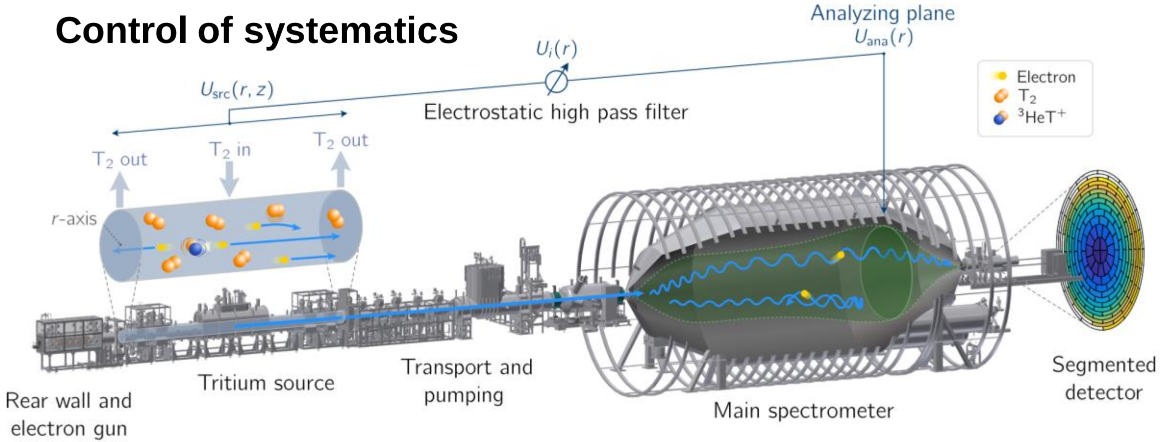
Experimental challenges:

- High source **activity, super-allowed transition**

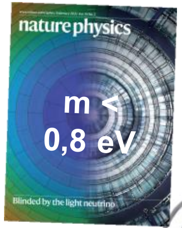
  ⇒ Tritium: $\boldsymbol{E_0}$ **= 18.6 keV**, $\boldsymbol{T_{1/2}}$ **= 12 yr**
- Excellent energy **resolution** (~1 eV)
- Low **background** (≪1 cps)
- **Control of systematics**



Tritium Laboratory Karlsruhe
safe tritium technologies &
versatile tritium analytics (> 30 yr)



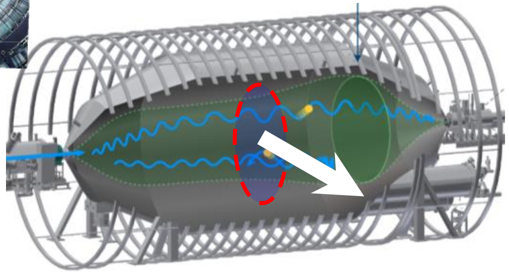
Experimental improvements wrg

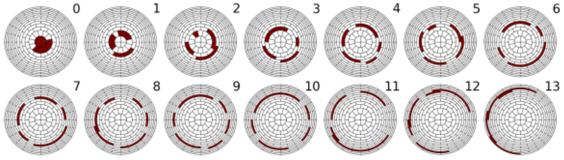


Nature Phys.
18 (2022) 160
Data of 2019

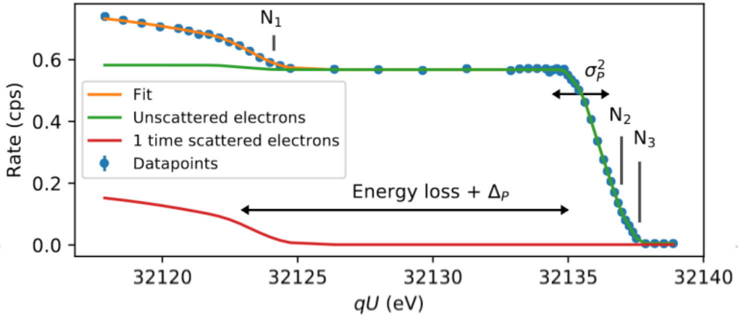
Karlsruhe Institute of Technology

- **Factor 6** more in statistics
- **Factor 2** lower **background** using "*shifted analyzing plane*" configuration
- **Precision calibration tools** available (Kr co-circulation with T-gas, novel e-gun)
- Detector **patches** to account for inhomogeneities
- **Improved** statistical sensitivity by optimized scan-time distribution
- **Systematic studies** e.g. measure Kr line widths to determine plasma parameters.
- **Eliminated** trapped particle backgrounds





Spectrum of $N_{1,2,3}$-32 lines of ^{83m}Kr



Systematic uncertainties

Statistical uncertainty dominates

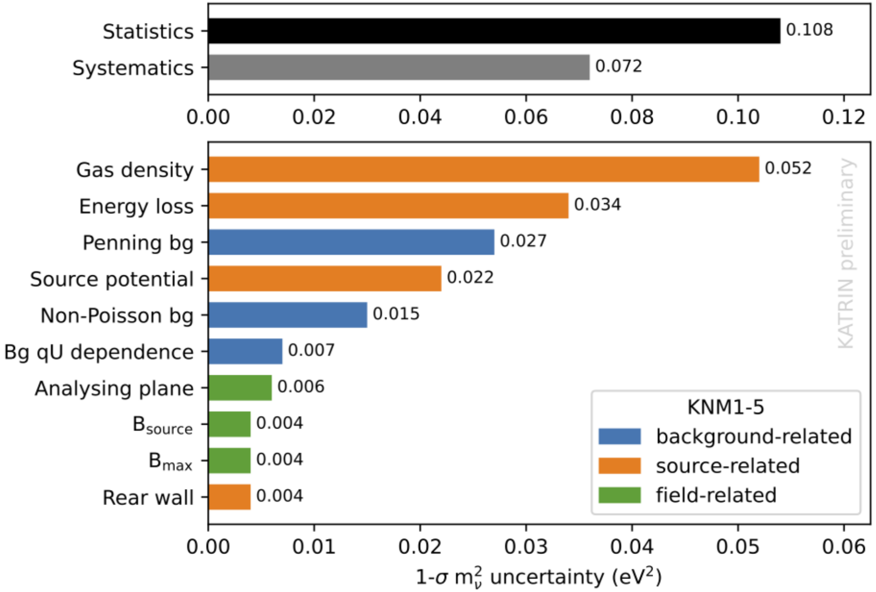
Significant reduction of the **background**-related systematics

Better control over source **scattering**

- Increased conservative uncertainties in this release
- Reduced uncertainties in following data

Reduction of the molecular **final-states** uncertainties

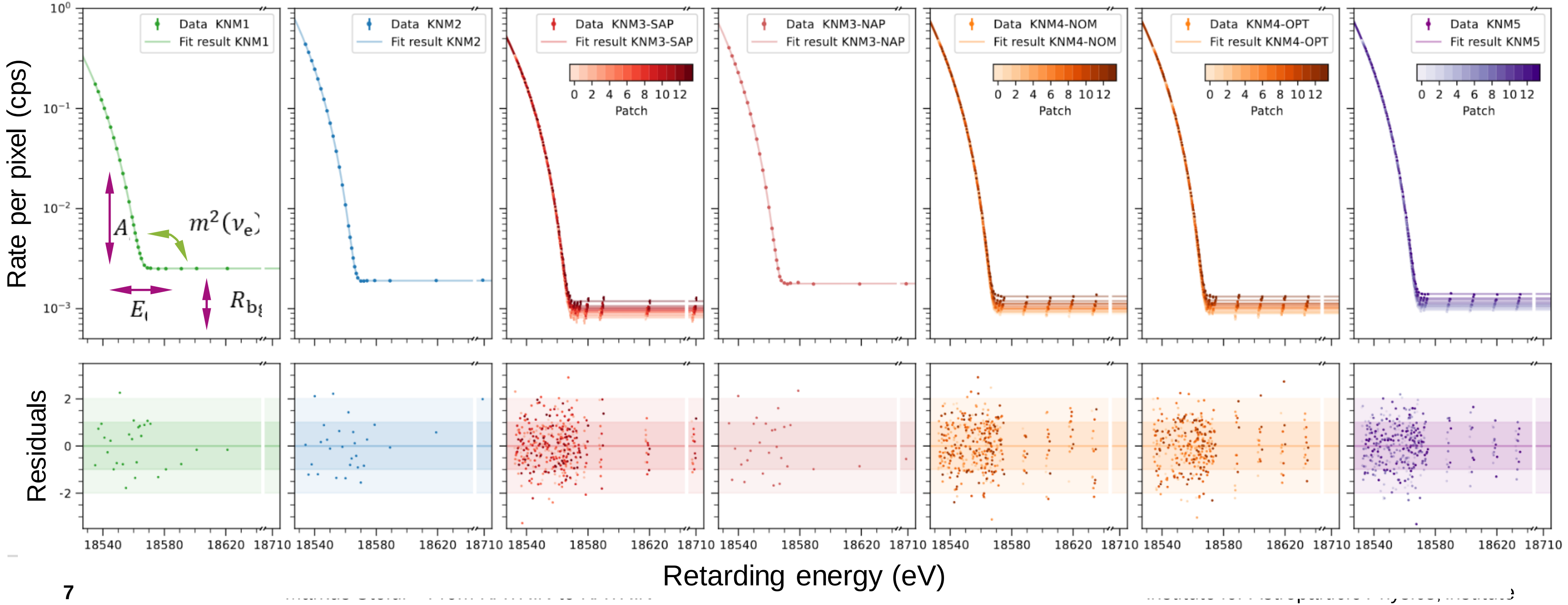
- Reassessment of theoretical uncertainty estimation: S. Schneidewind et al., Eur. Phys. J. C 84, 494 (2024)



→ further reduction of systematics for final neutrino mass analysis

Data & Fit result

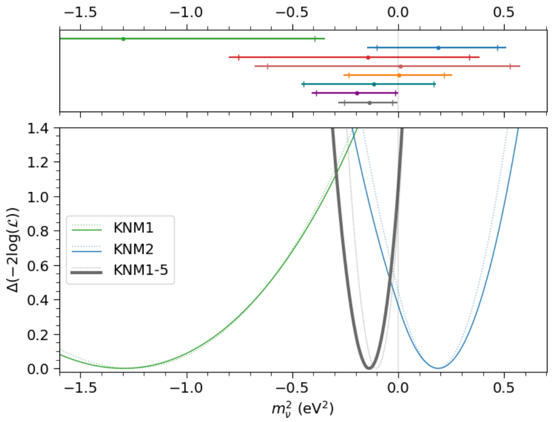
- Maximum likelihood **fit** with common $\boldsymbol{m_\nu^2}$ parameter in 59 data sets
- Excellent goodness-of-fit: **p-value=0.84**



Results

Best-fit value $m_\nu^2 = -0.14^{+0.13}_{-0.15}\,\mathrm{eV}^2$

Negative ***m²*** estimates allowed by the spectrum model to accommodate statistical fluctuations



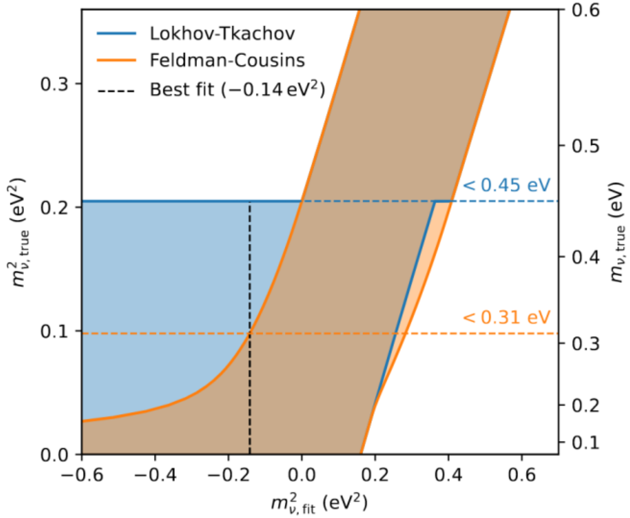
Lokhov-Tkachov construction

$$m_\nu < 0.45\,\mathrm{eV}\ \ (90\,\%\ \mathrm{CL})$$

KATRIN collab: arXiv:2406.13516

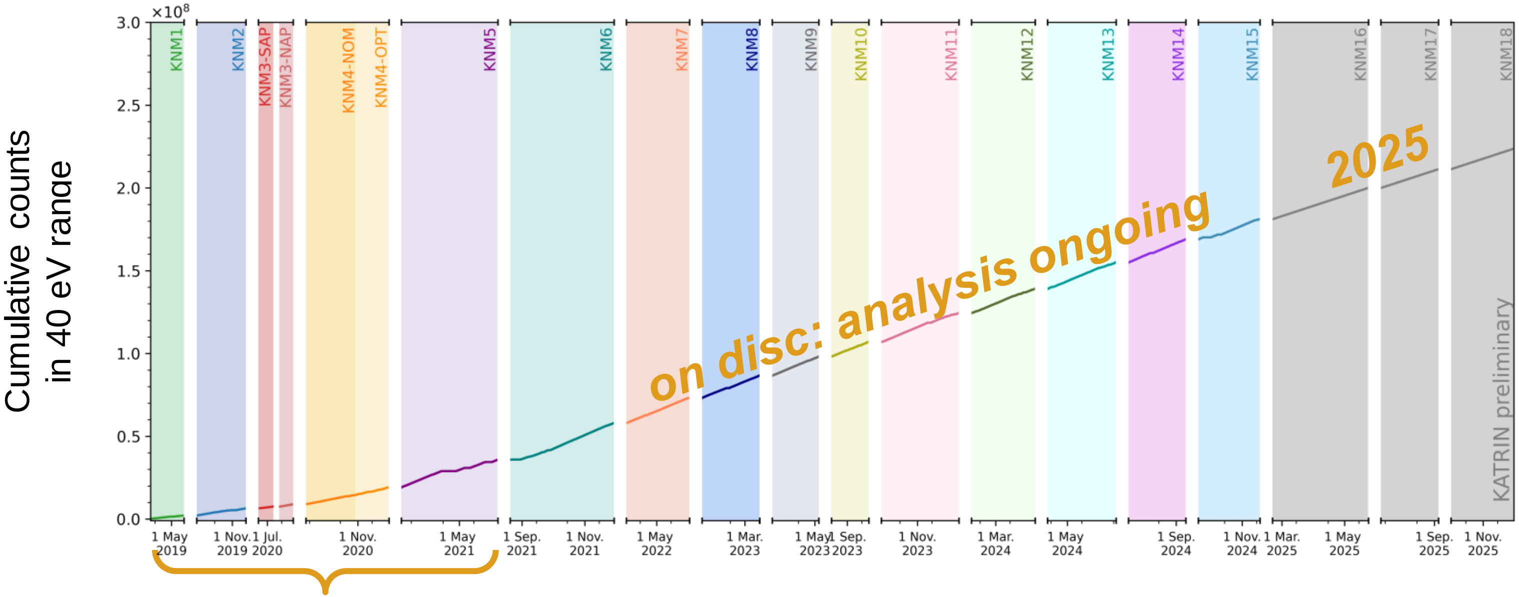
Feldman-Cousin $\boldsymbol{m_\nu}$ < 0.31 eV at 90 % CL

Bayesian analysis is in preparation



KATRIN data taking continues

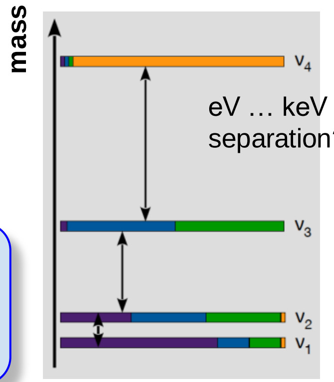
Meanwhile **~ 170 Mio** counts recorded – **x4.5** the statistics!
Another **50 Mio** to come in **2025** + calibration/systematics improvements



Sensitivity
m_ν < 0.3 eV

m_ν < 0.45 eV (90% C.L.)

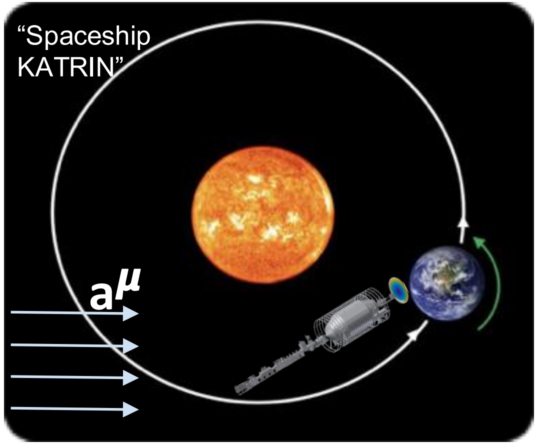
KATRIN “beyond neutrino mass”



β-spectrum of high statistics and precision

Is there a fourth (sterile) neutrino?
(search for a kink)

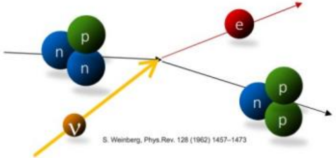
Phys.Rev.Lett. 126 (2021) 9, 091803
Phys.Rev.D 105 (2022) 7, 072004



Search for Lorentz invariance violation
(sidereal modulation)

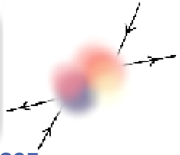
Phys.Rev.D 107 (2023) 8, 082005

Constrain local density of cosmic relic neutrinos
(peak search)

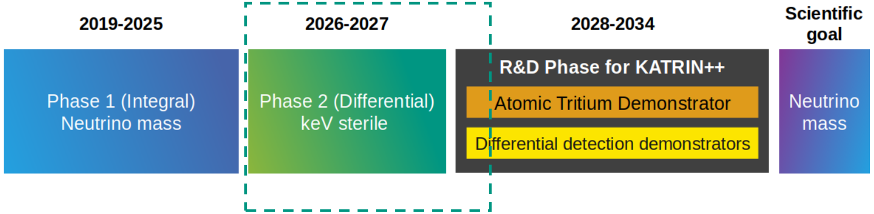


Phys. Rev. Lett. 129 (2022) 1, 011806

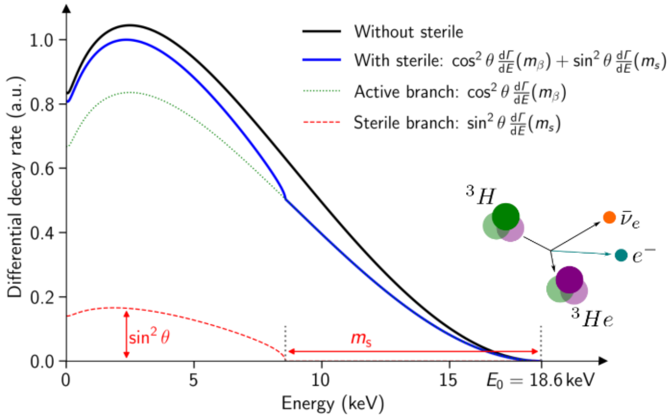
Search for exotic interactions
(spectrum shape)

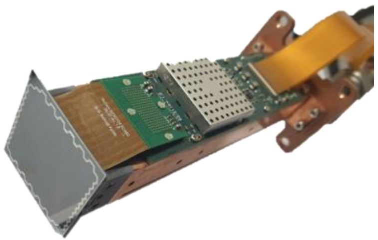


KATRIN collab., arXiv: 2410.13895



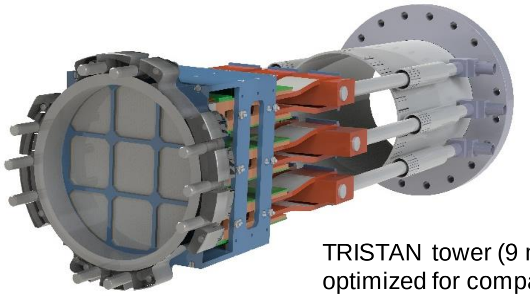
Differential: *energy determined directly by detector response, i.e. not by an integral scan of the spectrometer*





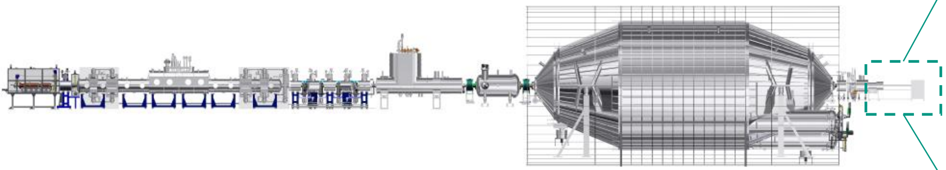
A TRISTAN module
Silicon Drift Detector with 166 pixels
Achieve Fano-noise limited perfromance
Max-Planck Institute of Physics, Munich
Halbleiterlabor Munich

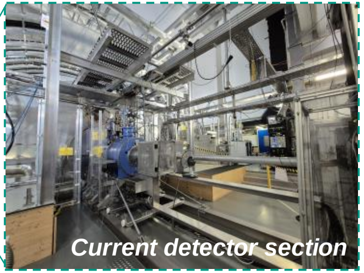
2 ASIC boards as frontend
Politecnico di Milano



TRISTAN tower (9 modules) optimized for compact insertion into beamline with cooling and keeping XUHV condition

- New **detector** and **data processing** (from 1 cps/pixel → 10^5 cps/pixel)
- New **beamline configuration** with **source modifications**
- New **analysis** methods required and new **systematic** effects involved





Setting up all equipment in 2025 in a new detector section; to be swapped in 2026.

2025: Pre-characterization of TRISTAN detector with calibration sources

Link to MT

New DAQ & Prepare data processing (1 TB/s streaming to backend), data and analysis management for ~50 TB/a

See also appendix

Arrival of first 3 detectors from Munich/Milano

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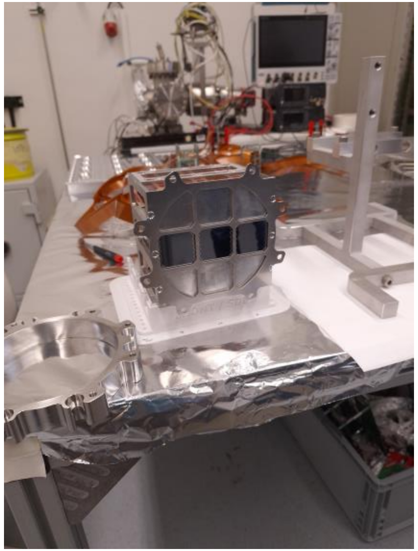
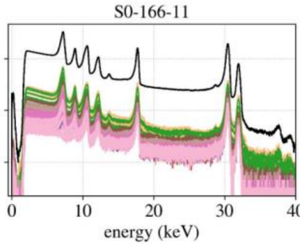
TRISTAN
module

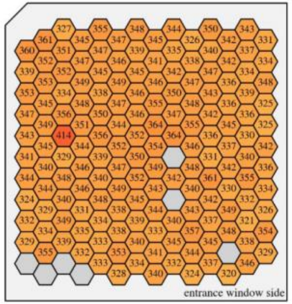


TRISTAN
tower with 9 modules
(here with 3 modules and
6 dummies)

Integration into
Beamtube inside
s.c.solenoid

Feedthrough chamber
for DAQ interface





First Light with
solid 83mKr source

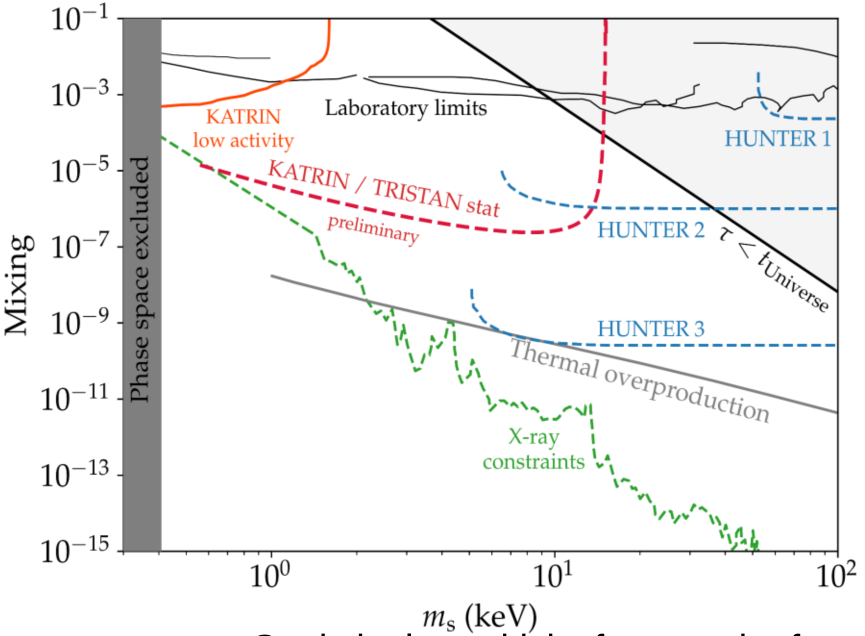
Differential measurements KATRIN with TRISTAN detectors

Unique opportunity for new scientific scope.

Hardware for installation in 2026 is on schedule.

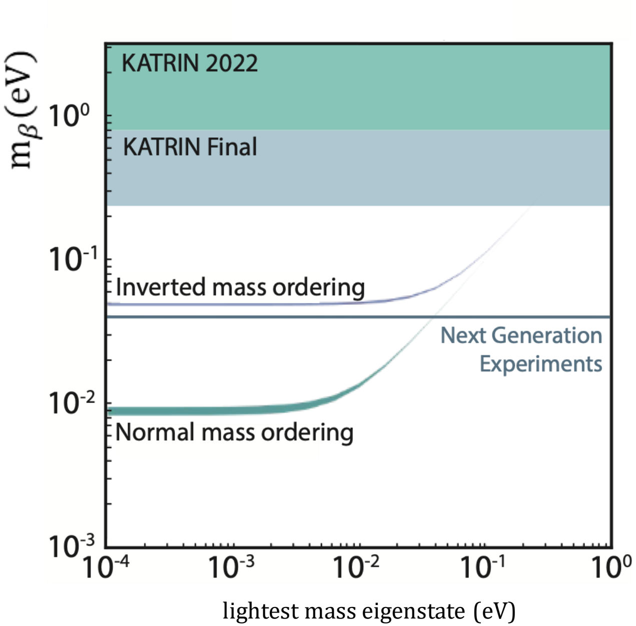
Additional challenges remain:

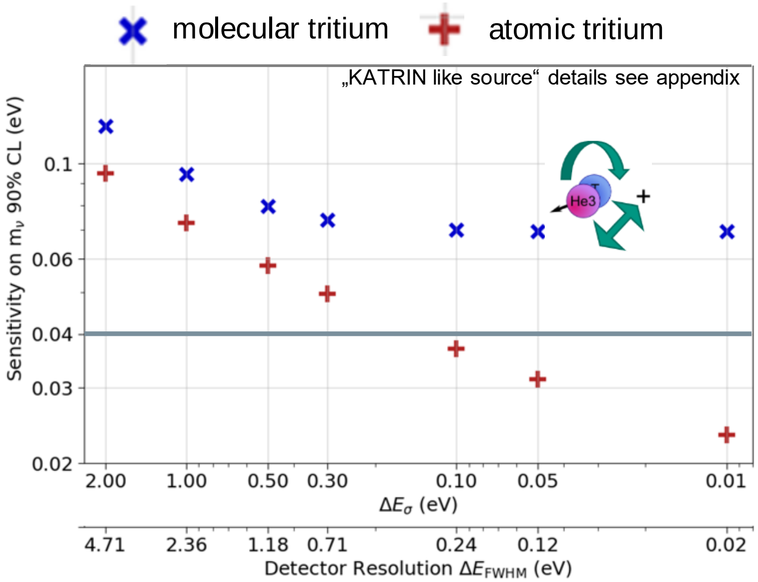
(data management, control and **treatment of limiting systematic effects by scattering**, implementation of new analysis & simulation mehtods)



Statistical sensitivity for search of sterile keV neutrinos

Prospects for direct neutrino mass measurement





Atomic tritium required

Energy resolution $\Delta E_\sigma < 0.3$ eV

R&D

KATRIN++

Initial R&D towards KATRIN++

- Atomic tritium at TLK

Aim for investigation

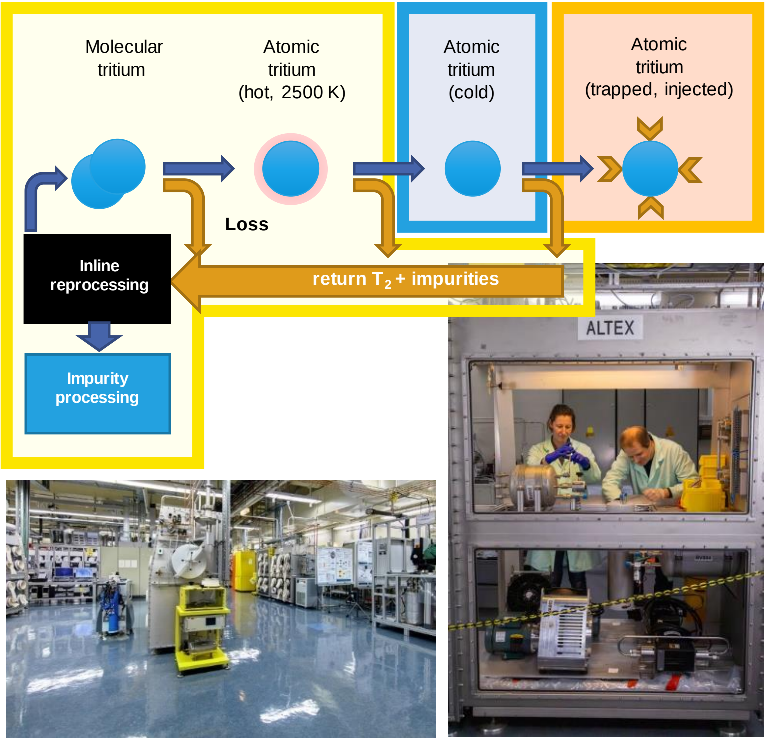
Develop atom cooling mechanism

Trapping times / max. densities

Interplay of beta-driven plasma (meV–eV)

and ultra-cold

trapped atoms (neV)



Tritium atom throughput on
the order of 10 g/day (c.f. KATRIN: 40 g/day)

Initial R&D towards KATRIN++

Cross-topic activity with MT, Contribution to InnoPool QS4Physics

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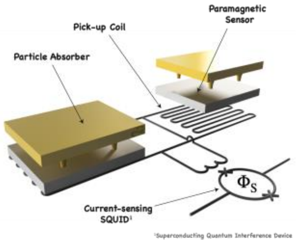
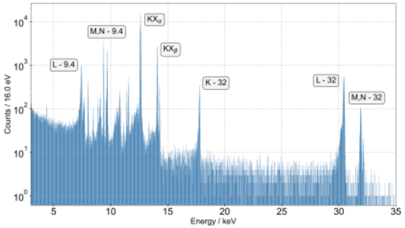
Quantum Sensors

Aim for investigation

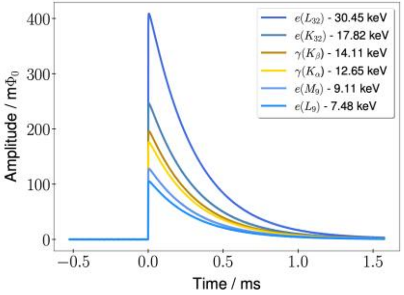
- Find suitable quantum sensors for energy measurement or Time-of-Flight methods
- Windowless coupling of mK-sensors to source/spectrometer on higher temperature
- Operation in magnetic fields (> 20 mT)

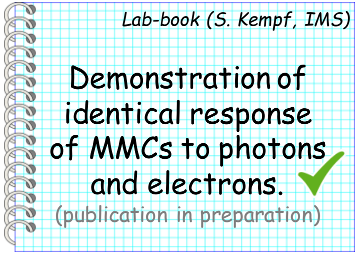
  Scaleability to sensitive areas o(100 cm²)





Candidate: Metallic Magnetic Microcalorimeters (MMCs)



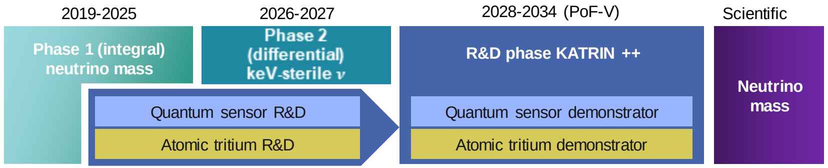


PoF-V

Use established MAC-E filter and KATRIN source technology to characterize quantum sensors
Use expertise and technical capabilities of existing TLK to develop atomic tritium source

Summary

- Release of m<450 meV (90% C.L.) based on ~20% of anticipated total data
- **Stable operation** of KATRIN & TLK: 80% of data for final analysis are on disc.
- Preparation in full swing for KATRIN with TRISTAN detectors → **new physics program**
- **Atomic tritium** and **quantum sensors** are key technologies for next generation (KATRIN++). Initial R&D started as seed for PoF-V.



Appendix

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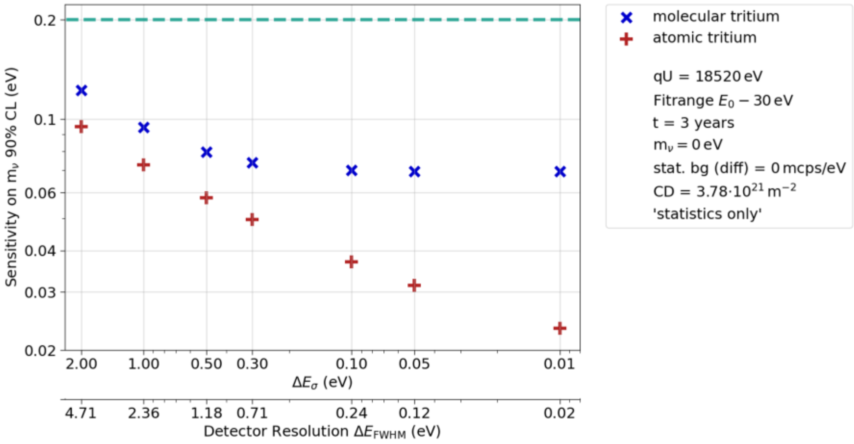

Input parameters for sensitivity simulation

This photo has been mirrored for better comparativity to other photo of slide.